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A comparison between wind speed distributions derived from the maximum entropy principle and Weibull distribution. Case of study; six regions of Algeria

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A B S T R A C T

The knowledge of the probability density function of wind speed is of paramount importance in many applications such as wind energy conversion systems and bridges construction. An accurate determination of the probability distribution of wind speed allows an efficient use of wind energy, thus rendering wind energy conversion system more productive. In the present paper, the maximum entropy principle (MEP) is used to derive a family of pre-exponential distributions in order to fit wind speed distributions. Using averaged hourly wind speed of six different regions in Algeria, it has been found that the proposed pre-exponential distributions fit the wind speed distributions better than the conventional Weibull distributions in terms of root mean square error. However, it has been found also that MEP based distributions have shown some practical limitations such as the choice of pre-exponential order and interval of definition.

Contents

1. Introduction

Wind plays a primordial role in many applications such as exploration of wind energy, bridge construction and the fight against desertification. Hence, the knowledge of wind characteristics is of great importance. When the probability density of the wind speed is known, their characteristics such as mean, variance and power density can be easily determined.

The Weibull distribution has been widely used to describe the probability density of the wind. According to Carta et al. [1], this density is the most used in the literature related to wind speed fitting and it is practically the only recommended distribution in books related to wind energy [2–4]. From many locations over the world of different topographies such as costal [5,6], mountainous [7] and flat regions [8], it has been shown that this distribution provides a good fitting of wind speed.

Recently, a new family of wind distributions based on the principle of the maximum entropy has been proposed as a new alternative to fit wind distribution. In 2004, Li and Li [9] have reported that the MEP based distributions are better than the Weibull distribution in term of root mean square error.

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The purpose of this paper is to apply this new approach to describe the probability density of the wind in Algeria for several sites characterized by different topographies. As a second purpose, we propose to compare the obtained distributions with the conventional Weibull ones. This comparison carried out not only in term of root mean square error, but also in terms of practical limitations of MEP distributions such as the definition interval and the choice of statistical constraints.

2. Weibull distribution

The Weibull distribution with two parameters is given by the following equation:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{1}$$

where v is the wind speed, c is the scale factor and k is the shape factor.

The scale factor c has the same dimension as the wind speed and it must be greater than zero. On the other hand, k is dimensionless. If $k=2$, the resulting function is often known by the Rayleigh distribution. However, if $k=3.6$ the Weibull distribution can be approximated by a Gaussian distribution [10]. For most wind conditions, k varies generally between 1.5 and 3 [1].

The parameters c and k can be estimated through various techniques such as the method of moments (MM), the graphical method (GM) and the method of maximum likelihood (ML). The MM and GM are among the simplest methods because they require little calculations only. However, it has been mentioned in [1] that the ML estimator provides the best estimation even if it requires a lot of iterative calculations. The ML estimators of form and scale factors are given by [1]:

$$\hat{k}_{\mathrm{ML}} = \left[\frac{\sum_{i=1}^{N} v_i^{\hat{k}} \ln(v_i)}{\sum_{i=1}^{N} v_i^{\hat{k}}} - \frac{1}{N}\sum_{i=1}^{N} \ln(v_i)\right]^{-1} \tag{2}$$

$$\hat{c}_{\mathrm{ML}} = \left[\frac{1}{N}\sum_{i=1}^{N} v_i^{\hat{k}}\right]^{1/\hat{k}_{\mathrm{ML}}} \tag{3}$$

where N is the number of wind speed samples.

In order to accelerate the calculations for the ML estimator, values obtained by the MM can be used as initial values of $\hat{c}$ and $\hat{k}$.

3. Maximum entropy principle (MEP)

The principle of maximum entropy based on maximization of Shannon's function S is widely used in information theory.

$$S = -\int_a^b f(v)\,\log(f(v)dv \tag{4}$$

Recently, it has been proposed to fit the distributions of wind speed in several world places such as the regions of Izmir and Elazig in Turkey [9,11], the Canarian Archipelago in Spain [12] and the region of Waterloo in Canada [13]. The authors in [11] have also considered data of Kansas City (USA) and Marmul (Oman).

The probability density function $f(v)$ can be obtained by minimizing the Shannon entropy within the following limits [9]:

$$\int_a^b f(v)dv = 1 \tag{5}$$

$$\int_a^b v^i f(v)dv = m_i \tag{6}$$

where m_i is the statistical moment of order i calculated empirically under the assumption that the wind possess is ergodic and stationary process:

$$m_i = \frac{1}{N}\sum_{i=1}^{N} v^i \tag{7}$$

A general solution of Eqs. (5) and (6) can be expressed as:

$$f(v) = \exp\left(\sum_{j=0}^{M} a_j v^i\right) \tag{8}$$

where $a_0, a_1, \ldots a_M$, are coefficients that must be estimated by solving the following system of equations:

$$\begin{aligned}
&\int_0^{v_{\max}} v\exp\left(\sum_{j=0}^{M} a_j v^i\right) dv = 1\\
&\int_0^{v_{\max}} v^1 \ \exp\left(\sum_{j=0}^{M} a_j v^i\right) dv = m_1\\
&\quad\vdots\\
&\int_0^{V_{\max}} v^M \ \exp\left(\sum_{j=0}^{M} a_j v^i\right) dv = m_M
\end{aligned} \tag{9}$$

where M is the order of greatest statistical moment and it is predetermined by the user.

Because a theoretical solution of the system of Eq. (9) is practically impossible therefore, the use of numerical methods is necessary. The system of Eq. (9) can be solved using Newton–Raphson method.

To obtain better precisions, author in [11] has introduced a pre-exponential term to the distributions MEP. The resulting distributions are known as MEP-type distributions and they are given by:

$$f(v) = v^r \ \exp\left(\sum_{j=1}^{M} a_j v^i\right) \quad r \geq 0 \tag{10}$$

where r is the order of the pre-exponential term.

4. Hybrid distribution

The hybrid distribution is used when the frequency of calm spells recorded on a given site is greater than or equal to 15%. Indeed, this proportion cannot be neglected and must be taken into account when characterizing wind speed. The hybrid distribution is given by:

$$f_h(v) = \begin{cases} ff_0 & v = 0 \\ (1 - ff_0)f(v) & v \neq 0 \end{cases} \tag{11}$$

where $f(v)$ is the probability density for nonzero velocities and ff_0 is the frequency of calms.

5. Wind power

In many application areas such as wind power and construction of structures, the distribution of wind speed is used to estimate the

Table 1
Geographical coordinates altitude and climatic characteristics of the regions under consideration.

Region	Coordinates and altitude	Climate characteristics
Annaba	(36.8°N, 7.8°E), 4 m	**South Mediterranean climate**
Oran	(35.6°N, 0.6°W), 90 m	Wet-winter, dry-summer. Land/water differences play a large part on air flow.
Batna	(35.5°N, 6.2°E), 914 m	**Dry mid-latitude climate** Semiarid climate. Mountains ranges trap cold air in winter, making winters very cold. Summers are warm to hot.
Ghardaïa	(32.4°N, 3.8°E), 450 m	**Dry climate** (semi-arid) Very low precipitations, heavy sandy winds in spring (Mars, April and Mai).
Inamenass	(28.0°N, 9.6°E), 562 m	**Dry sub-tropical climate**
Adrar	(27.9°N, 0.3°W), 263 m	Desert found in low Latitude between 18° and 28°. They coincide with the edge of the equatorial subtropical high pressure belt and trade winds.

Table 2
Some descriptive measures of wind speed at the sites studied.

	m_1(m/s)	m_2(m/s)^2	m_3(m/s)^3	m_4(m/s)^4	v_{max}(m/s)
Annaba	3.60	18.40	115.55	836.06	16.1
Oran	3.63	20.73	154.80	1474.21	26.5
Batna	3.58	20.38	146.10	1250.36	18.6
Ghardaïa	3.62	22.01	157.82	1311.35	19.7
Inamenass	4.74	30.76	242.38	2265.61	25.8
Adrar	6.30	49.44	453.04	4779.65	31.1

wind power. For a surface $A = 1\,\text{m}^2$, the wind power is given by the following ratio [11]:

$$E(v) = \frac{1}{2}\rho v^3 f(v) \tag{12}$$

where ρ is the density of air ($\rho = 1.225\,\text{kg/m}^3$ in the standard conditions).

6. Results and discussions

In this section we consider the determination of the probability densities using the two distributions mentioned above for six different sites of Algeria (Fig. 1). The used data are hourly measured over two years (January 2006–December 2007). In addition to the geographical coordinates and the altitude above sea level for each region under consideration, Table 1 also presents a brief description of the typical climate of each region.

Table 2 provides descriptive measures of wind speed at the studied sites. As it can be seen in Table 2, coastal sites in Algeria are characterized by a low potential while the internal sites (South) are most suitable for wind energy conversion systems. Such results have been motioned in several studies such as [8,14] and [15].

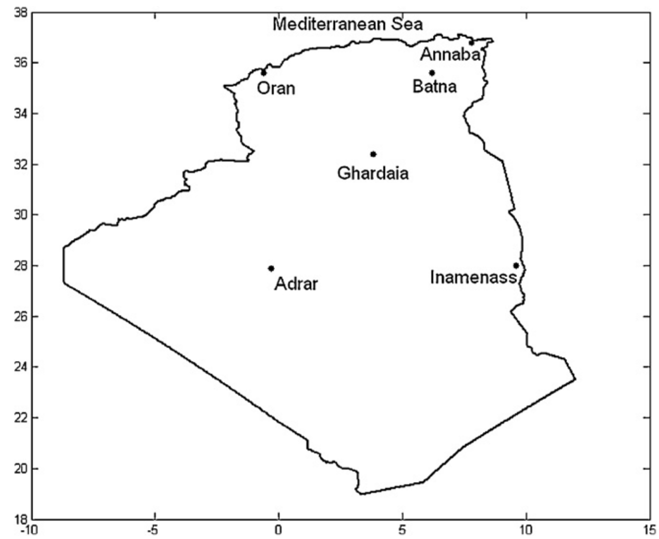

Fig. 1. Map of Algeria.

The evaluation of histograms of the data revealed that the frequencies of calm in the regions of Batna and Ghardaïa exceed 15%. To take this into consideration, hybrid distributions (Eq. (11)) are developed for these two sites.

Table 3 shows the RMSE of Weibull distributions and MEP/type-MEP for the studied regions. We denote by P-RMSE the root mean

Table 3
The error of Weibull distributions and MEP/type-MEP for proposed sites. Distributions with the minimum RMSE and P-RMSE are bold.

	Annaba		Oran		Batna		Ghardaia		Inamenass		Adrar	
	RMSE v	P-RMSE $\rho v^3/2$	RMSE v	P-RMSE $\rho v^3/2$	RMSE v	P-RMSE $\rho v^3/2$	RMSE v	P-RMSE $\rho v^3/2$	RMSE v	P-RMSE $\rho v^3/2$	RMSE v	P-RMSE $\rho v^3/2$
WD	0.02331	0.87827	0.02715	1.25193	0.05411	1.37024	0.02867	2.54721	0.02953	2.53351	0.02679	5.84563
MEP												
$M = 2$												
$r = 0$	0.03182	0.61998	0.02844	1.10955	0.04219	0.9499	0.03108	2.84946	0.03177	1.87365	0.03049	5.26051
$r = 1$	**0.02141**	0.87489	0.03317	1.5839	0.03670	0.70262	0.02751	2.50504	0.03206	1.38601	0.02807	4.31085
$r = 2$	0.01997	1.41797	0.04138	1.91178	0.03415	0.62163	0.02419	2.19157	0.03237	**1.37044**	0.02585	3.64223
$r = 3$	0.02588	1.90039	0.05153	2.29305	0.03458	0.76189	0.02108	1.90926	0.0329	1.61312	0.02381	3.14913
$r = 4$	0.03454	2.31790	0.06183	2.70499	0.03756	1.02782	0.01819	1.66035	0.03434	1.99249	**0.02189**	**2.81299**
$M = 3$												
$r = 0$	0.02832	0.72039	**0.02634**	1.01625	0.04086	0.84949	0.01992	2.05322	**0.02875**	1.40693	0.02496	4.01441
$r = 1$	0.02866	**0.37901**	0.03429	1.63904	0.03696	0.70777	0.01826	1.88159	0.03469	1.78515	0.02670	3.99841
$r = 2$	0.03134	0.43557	0.04168	2.00560	0.03377	0.59602	0.01691	1.73215	0.03919	2.2156	0.02860	4.25525
$r = 3$	0.03416	0.66090	0.04731	2.33042	0.03116	0.52487	0.01585	1.60356	0.04281	2.6066	0.03034	4.55802
$r = 4$	0.03685	0.89946	0.05189	2.60886	**0.02906**	0.50203	0.01508	1.49451	0.04594	2.96134	0.03196	4.87118
$M = 4$												
$r = 0$	0.02419	0.54859	0.02762	**0.89459**	0.03647	0.69191	**0.01050**	**1.06572**	0.03054	1.72306	0.02577	4.24587
$r = 1$	0.03092	0.49272	0.03599	1.30651	0.03450	0.63394	0.01090	1.07975	0.03757	2.2576	0.02932	4.7715
$r = 2$	0.03573	0.56337	0.04382	1.6434	0.03262	0.58094	0.01134	1.09615	0.0425	2.69767	0.03181	5.20526
$r = 3$	0.03952	0.70607	0.04984	1.93321	0.03082	0.53474	0.01181	1.11430	0.04637	3.08042	0.03385	5.59519
$r = 4$	0.04261	0.87303	0.05445	2.19015	0.02909	**0.49777**	0.01231	1.13386	0.04961	3.42193	0.03563	5.95387

Table 4
Values of parameters and their standard error of Weibull and MEP/MEP-type distributions (best MEP/type-MEP are presented only).

	Parameters of Weibull	Standard error	Parameters of MEP/type-MEP
Annaba ($r=1$)	$k=1.8011$ $c=4.2837$	1.0602×10^{-2} 3.4053×10^{-2}	$\hat{a}_0=-0.90589$ $\hat{a}_1=-1.0169$ $\hat{a}_2=1.8389\times10^{-2}$
Oran ($r=0$)	$k=1.3402$ $c=4.1592$	7.8892×10^{-3} 3.3063×10^{-2}	$\hat{a}_0=-1.8694$ $\hat{a}_1=1.27658$ $\hat{a}_2=-4.9996\times10^{-2}$ $\hat{a}_3=1.3098\times10^{-3}$
Batna ($r=4$)	$k=1.8863$ $c=4.8667$	1.1104×10^{-2} 3.8687×10^{-2}	$\hat{a}_0=-0.6105$ $\hat{a}_1=-2.1199$ $\hat{a}_2=1.2623\times10^{-1}$ $\hat{a}_3=-4.0579\times10^{-3}$
Ghardaïa ($r=0$)	$k=2.3611$ $c=5.7264$	1.3899×10^{-2} 4.5522×10^{-2}	$\hat{a}_0=-7.3739$ $\hat{a}_1=3.5710$ $\hat{a}_2=-7.2149\times10^{-1}$ $\hat{a}_3=5.4830\times10^{-2}$ $\hat{a}_4=-1.4980\times10^{-3}$
Inamenass ($r=0$)	$k=2.0922$ $c=5.8427$	1.2316×10^{-2} 4.6446×10^{-2}	$\hat{a}_0=-2.77935$ $\hat{a}_1=0.448795$ $\hat{a}_2=-6.8140\times10^{-2}$ $\hat{a}_3=1.4648\times10^{-3}$
Adrar ($r=4$)	$k=2.4625$ $c=7.4863$	1.4496×10^{-2} 5.9512×10^{-2}	$\hat{a}_0=-3.89781$ $\hat{a}_1=-0.92934$ $\hat{a}_2=8.6525\times10^{-2}$

Table 5
Values of the empirical moments compared to the theoretical moments computed via Wiebull and MEP/type-MEP distributions (best MEP/type-MEP are presented only).

	Empirical moments	Theoretical moment via WB	Theoretical moment via MEP/type-MEP
Annaba ($r=1$)	$m_0=1$ $m_1=3.6$ $m_2=18.4$	1 3.8089 19.295	1 3.6005 18.4011
Oran ($r=0$)	$m_0=1$ $m_1=3.63$ $m_2=20.73$ $m_3=154.8$	1 4.0206 22.5864 157.6541	0.9997 3.63 20.7301 154.8008
Batna ($r=4$)	$m_0=1$ $m_1=4.29$ $m_2=24.42$ $m_3=175.09$	0.9864 4.3151 24.3213 163.5835	1.0195 4.319 24.5464 176.1559
Ghardaia ($r=0$)	$m_0=1$ $m_1=5.07$ $m_2=30.86$ $m_3=223.14$ $m_4=1908.31$	1 5.0744 31.0576 216.6831 1671.9437	1 5.07 30.7906 220.7772 1834.4678
Inamenass ($r=0$)	$m_0=1$ $m_1=4.74$ $m_2=30.76$ $m_3=242.38$	1 5.1751 33.5303 253.3982	0.9999 4.74 30.7598 242.3743
Adrar ($r=4$)	$m_0=1$ $m_1=6.3$ $m_2=49.44$	1 6.6399 52.3834	1 6.3 49.4398

square error of the power density distribution. The MEP-type distributions are developed for values of M ranging between 2 and 4 and for those of r, which varies between 1 and 4.

6.1. MEP distributions ($r=0$)

According to the obtained results, it can be noticed that the MEP distributions can adjust the probability densities of the wind speed better than Weibull for several sites and for several values of M. In 50% of considered cases, the RMSE of MEP distributions are below those of Weibull distributions. Only in case of Annaba region, the MEP distributions could not deliver better results, even for different values of $M=2$, 3 and 4. Regarding the density of wind power, Table 3 indicates that for more than 77% of the cases studied, the MEP distributions offer lower P-RMSE than the Weibull distribution. In the case of Annaba, it is interesting to note that even though the Weibull distribution fits better the probability density of wind speed, Table 3 indicates that the MEP distributions show lower P-RMSE ($M=2$, 3 and 4). This can be attributed to error introduced by the frequency of calm for the probability density. This error tends to zero for the power density thanks to the term v^3 (Eq. (12)).

6.2. MEP distributions ($r \neq 0$)

For the MEP-type distributions, the results indicate that for the six studied sites, the MEP-type distributions offer better performances for several values of M and r. However, we would like to mention that an increase in r or M do not yield systematically to better adjustments (Table 3). The values of M and r that provide the best fitting are shown in bold in Table 3. Yet, it is very difficult to determine a rule which gives the optimal configuration of M and r that yield the better adjustment of wind speed distribution.

Similarly to the MEP distributions, the best fitting of wind speed by MEP-type does not necessarily yield the best fitting of the power

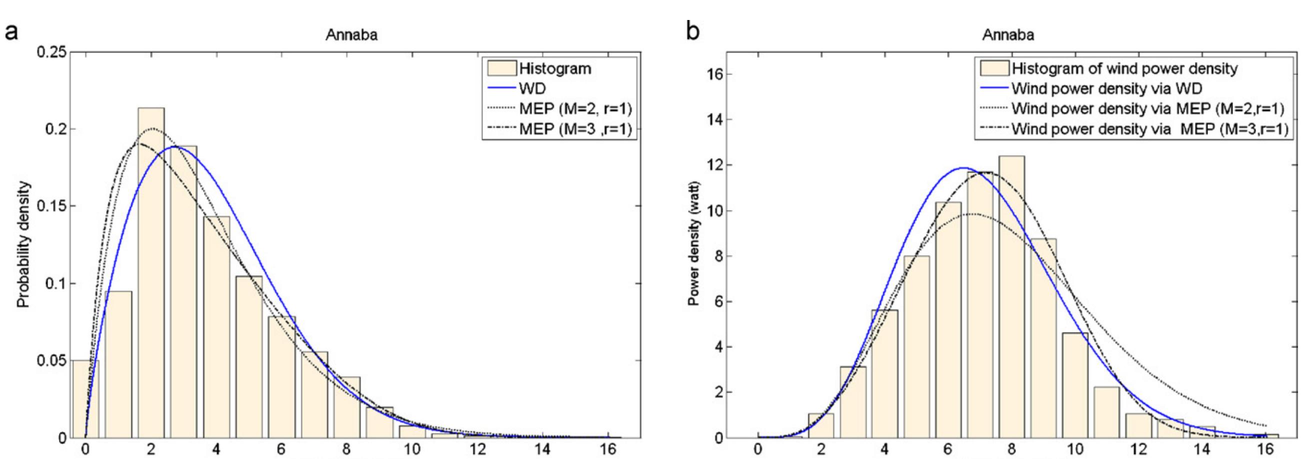

Fig. 2. Comparison between MEP-type and the Weibull distributions for the region of Annaba. (a) The probability density of wind speed. (b) The power density of wind speed.

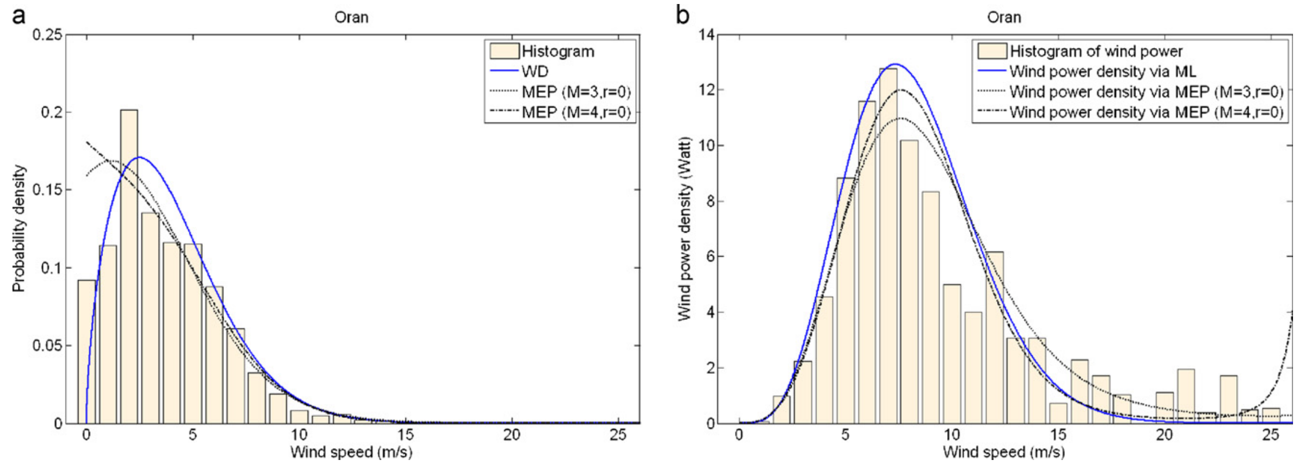

Fig. 3. Comparison between MEP-type and the Weibull distributions for the region of Oran. (a) The probability density of wind speed. (b) The power density of wind speed.

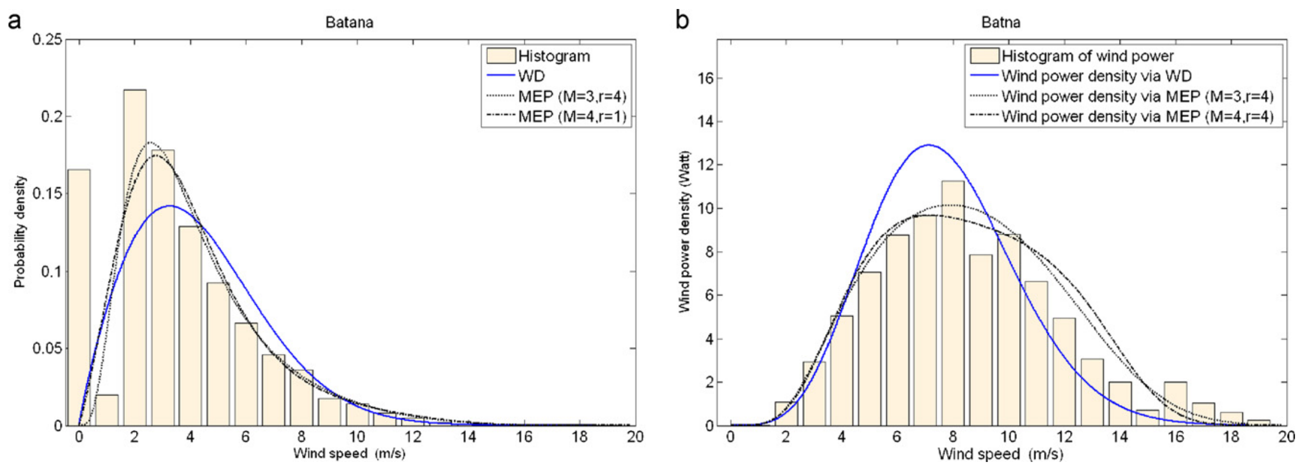

Fig. 4. Comparison between MEP-type and the Weibull distributions for the region of Batna. (a) The probability density of wind speed. (b) The power density of wind speed.

density. Such results have been mentioned also in the previous studies [11].

It is important to mention that the values of P-RMSE are always higher than RMSE of wind speed. Similar to results achieved in [11] and [13]. Indeed, this is due to term v^3.

In Table 4, we present the values and standard errors of parameters of Weibull and MEP/MEP-type distributions (results of best distributions are presented only). While in Table 5, we present their corresponding statistical moments (empirical and theoretical). It is very clear that the distributions MEP/MEP-type provide the best fitting of the experimental moments.

For the six sites studied, Figs. 2–7 show the histograms, the Weibull distributions the MEP/MEP-type distribution having the minimum RMSE and P-RMSE. We note that the MEP-type

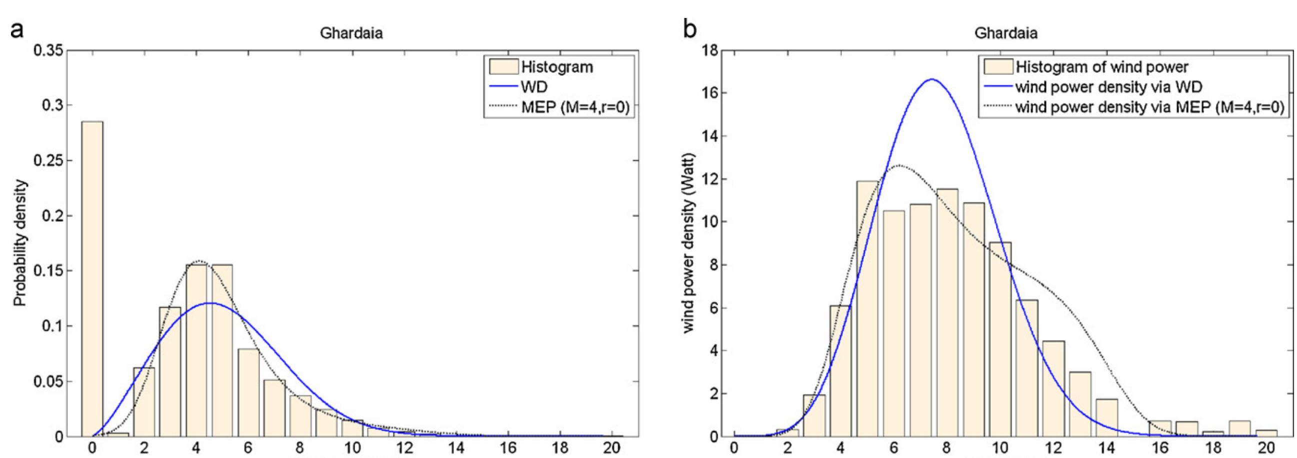

Fig. 5. Comparison between MEP-type and the Weibull distributions for the region of Ghardaia. (a) The probability density of wind speed. (b) The power density of wind speed.

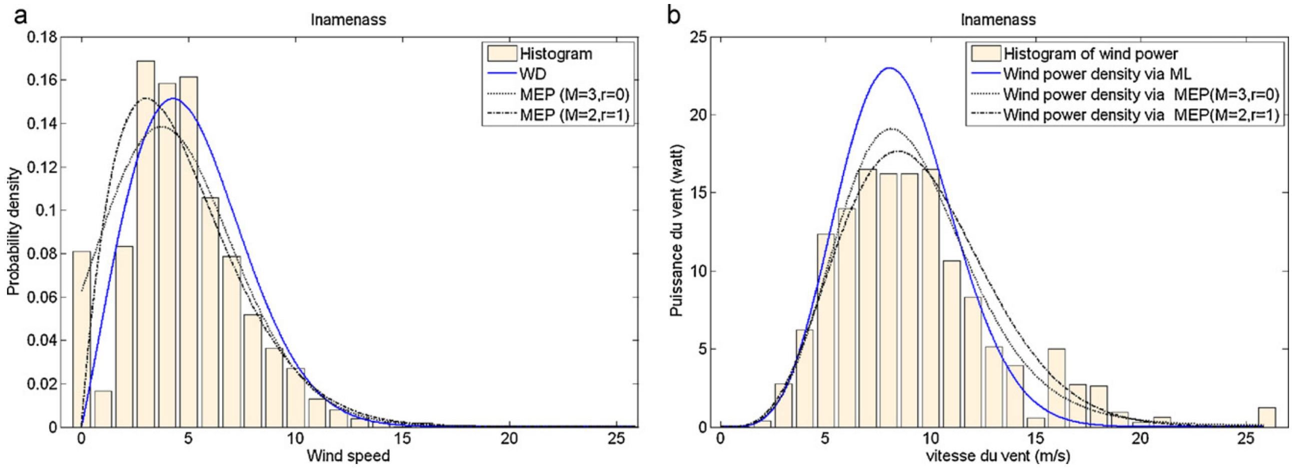

Fig. 6. Comparison between MEP-type and the Weibull distributions for the region of Inamenass. (a) The probability density of wind speed. (b) The power density of wind speed.

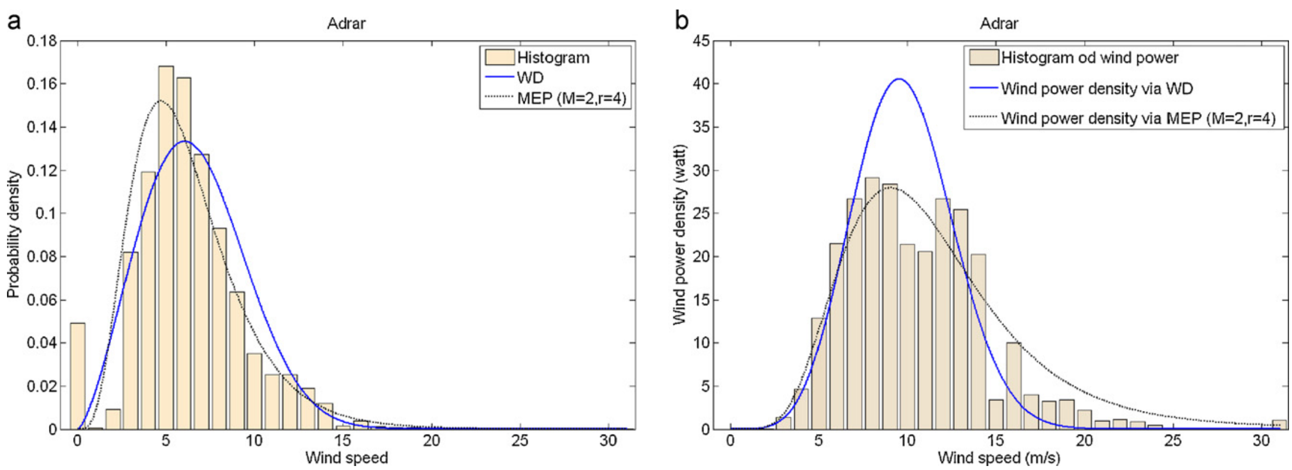

Fig. 7. Comparison between MEP-type and the Weibull distributions for the region of Adrar. (a) The probability density of wind speed. (b) The power density of wind speed.

distributions are more appropriate to adjust histograms of wind speed in most studied cases (Annaba, Batna, Ghardaia and Adrar) especially for speeds of wind between 5 and 15 m/s. For regions of Oran and Inamenass, it was found that the MEP distributions describe better the distribution of wind speed, especially in periods of calms ($v = 0$ m/s); they can start with non-zero values (but not necessarily), which is not the case for the Weibull distribution and the MEP-type that must necessarily cross the origin $(x, y) = (0, 0)$.

Concerning the power densities of wind, the results indicate that the distributions MEP/MEP-type are more suitable to fits the wind power notably for renewable energy applications (speeds between 5 and 15 m/s). For the region of Oran, the power density MEP (Fig. 3b) shows a divergence for large values of v. This can be explained by the fact that these distributions are optimized to fit the probability densities of the wind speed whereas they are used to describe the power of wind. Furthermore, those distributions are optimized for very specific wind speed intervals. Beyond these intervals, the behaviors of those distribution are very difficult to predict (unlike the Weibull distributions, which tend to zeros for large values of v).

7. Conclusion

In this work, we derived probability distributions from the principle of maximum entropy to fit wind speed as well as wind power. As results, it has been found that these distributions can provide a better alternative than the Weibull distribution. For the six sites studied, the performances of the proposed distributions have exceeded those of Weibull distributions.

Although it has been found that the maximum entropy based distributions provide better fitting of wind speed, we should mention that they are difficult to handle; the choice of the optimal distribution among a lot of possible configuration is not evident. Similarly to the previous studies, we have found that the increase of the statistical constraints as well as of the pre-exponential term v^r is not systematically beneficial in terms of performance. It has been also found that a good fitting of the probability density does not imply automatically a good fitting of the power density.

Finally, it is useful to note some inconvenient encountered in the development and calculations MEP/MEP-type distribution. Firstly, these distributions require lot of computations to be solved. Secondly, there are no general rules that determine the optimal values of M and r. So we must try different combinations to decide the best distribution. Thirdly, those distributions are optimized for specific intervals of wind speed, beyond those intervals, their behaviors is completely unpredictable.

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